

GLACIER AND CLIMATE EVOLUTION IN THE PARIACACÁ MOUNTAINS, PERU

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ABSTRACT. *Glaciers in Peru play a major role in water availability and they also have direct implications on natural hazards such as glacial lake outburst floods (GLOFs) and/or ice avalanches, which have caused a high number of fatalities and damage to infrastructure in the last decades. Despite a noticeable effort to quantify and understand the shrinking and thawing of glaciers in Peru, there are still regions where detailed assessment is still missing.*

In this work, a set of remote sensing images were used to map, for the first time, the evolution of the glaciated area (from 1970 to 2018) in the Pariacacá Mountains (11°5' S, 76°0' W) in the Cordillera Central of Peru. The results evidenced a marked decrease of the glaciated surface, with 55.3% shrinkage since 1970 and 40% since 1987. Faster glacier retreat occurred between 1985 and the end of the 1990s, and this period was followed by a significant slowdown in shrinking rates. The differential loss of ice, depending on elevation and exposure to incoming radiation, has led to changes in spatial distribution of the glaciers. Currently, they have almost completely thawed below 5000 m a.s.l. They are mostly located in south- to west-facing aspects. Ice melting in the last decades has even affected the summit areas. Finally, the development of ablation hollows has been identified as an important driver of glacier thaw. These features are formed mainly in gentle slopes and highly irradiated zones between 5000 and 5400 m a.s.l.

Evolución glaciar y climática en las montañas de Pariacacá, Perú

RESUMEN. *Los glaciares en Perú juegan un papel fundamental en la disponibilidad de agua y también poseen claras implicaciones en la ocurrencia de riesgos*

naturales como desbordamientos de lagos (GLOFs) y/o avalanchas de hielo que han causado un gran número de víctimas y daños a infraestructuras en las últimas décadas. A pesar del gran esfuerzo que se ha realizado para cuantificar y comprender el retroceso de los glaciares en Perú, aún existen regiones donde se carece de un estudio detallado.

En este trabajo, se utilizan imágenes de satélite para cartografiar por primera vez la evolución de la superficie cubierta por glaciares (durante el periodo 1970-2018) en las montañas de Pariacacá (11°5' S, 76°0' W) en la Cordillera Central de Perú. Los resultados evidencian un marcado retroceso glaciar, afectando al 55.3% desde 1970 y al 40% desde 1987. El periodo de mayor retroceso sucedió entre 1985 y el final de los años 90, periodo seguido por una ralentización en los ratios de fusión. Las diferencias en desaparición de hielo según altura y orientación han llevado a claros cambios en la distribución espacial de los glaciares. Actualmente, se encuentran mayoritariamente en caras sur y este. La desaparición de hielo ha llegado a afectar en los últimos años a los sectores cimeros. Finalmente, también se ha analizado la evolución de grandes depresiones de fusión sobre los glaciares que han sido identificados como un elemento significativo para acelerar la degradación de los glaciares. Estas formas aparecen fundamentalmente en zonas con elevada radiación, entre los 5000 y 5400 m s.n.m.

Key words: Glaciers, Remote sensing, glaciated area, ablation hollows, Pariacacá Mountains, Peru.

Palabras clave: glaciares, teledetección, superficie glaciada, depresiones de fusión, Cordillera Pariacacá, Perú.

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1. Introduction

Peru hosts the largest area occupied by tropical glaciers in the world. They play a significant role in the supply of water, not only for local communities living in the Andes, but also for large irrigated and urban areas located in the lowlands, including the megacity of Lima and big cities such as Cuzco, Arequipa and Huancayo among others (Vuille *et al.*, 2003). Since the end of the Little Ice Age (LIA), Peruvian glaciers have been thawing, and this trend accelerated after 1970 (Juen *et al.*, 2007). Thus, more than 40% of the glaciated area has vanished, from the early 1980s to the present time (Schauwecker *et al.*, 2014; Emmer, 2017). Thawing has particularly affected areas below 5000 m a.s.l. (Silverio and Jaquet, 2017), where the lost glacier surface exceeded

80% (Veettil *et al.*, 2017). Glacier changes have already manifested, with shifting river regimes (Mark *et al.*, 2017), the apparition of new lakes (Emmer *et al.*, 2018), changes in erosion processes impacting water quality and numerous catastrophic events, mainly related to glacial lake outburst floods (GLOFs) (Haerberli *et al.*, 2016; López-Moreno *et al.*, 2017).

Recent deglaciation has affected all mountain ranges in Peru, without exception, but the shrinkage rate differs remarkably between analysed areas. For example, (Veettil and de Souza, 2017) reported a loss of 52.2% and 44% of surface covered by ice during the periods 1975-2015 and 1985-2015 respectively for the Cordillera Vilcanota. Veettil *et al.* (2018) reported a decrease of 50%, 56%, 30% and 56.7% for Huagaruncho, Huaytapallana, Vilcamba and Urumba, respectively, for the period 1985-2015. López-Moreno *et al.* (2014) also reported a loss of 56% of ice cover of the Huaytapallana Mountains for the period 1987-2013. Kochtitzky *et al.* (2018) reported a reduction of 24% in the Coropuna region for the period 1984-2014. Silverio and Jaquet (2017) reported a 27.3% of ice loss in Cordillera Blanca between 1985 and 2016; while other smaller ranges have lost more than 70% of ice since 1970, as is the case for La Viuda, La Raya, Huanzo and Chila ranges (ANA, 2014). These differences suggest that climate variables may exhibit a different evolution in the different ranges, but it is also possible that glaciers in different mountains respond differently to changing climate as a consequence of their hypsometry and topographic context (López-Moreno *et al.*, 2006; Veettil *et al.*, 2018). Despite the increasing number of studies on glacier evolution in Peru (Rabatel *et al.*, 2013; Vuille *et al.*, 2018), there are still sectors with a noticeable surface covered by glaciers that have been only marginally studied. This is the case of the Pariacacá Mountains in the Cordillera Central, where detailed reconstruction of the recent evolution of the ice-covered surface is still lacking.

This study shows the evolution of glaciers in the Pariacacá mountain range from 1970 to 2018, based on remote sensing imagery. The interannual evolution of the glaciers was contextualized with the topographic characteristics of the recently deglaciated area and also with the climate evolution observed during the study period. Additionally, the spatial distribution of ablation hollows on the glaciated surfaces was quantified and analysed. Ablation hollows are common features in many glaciers of the world, but they are particularly abundant and well represented in the Pariacacá Mountains. They clearly influence the acceleration of glacier thaw, but their presence is still poorly understood.

2. Study area

The Pariacacá Mountains (Fig. 1) are part of the Peruvian Central Cordillera located between Junín (eastward) and Lima (westward) Departments of Peru (11°5 S, 76°00' W). With approximately 30 km length and an average width of 15 km, the Pariacacá mountain range extends north to south from a plateau at 4000 m a.s.l. The origin of these granitic mountains is tectonic, with no presence of vulcanos in this area. The highest elevation is found at Pariacacá Sur peak (5750 m a.s.l.), and more than 30 peaks exceed 5000 m. The mountains drain to the Pacific through Cañete, Mala and

Rimac rivers, the latter supplying water to Callao and Lima cities. Population density is very low, the main settlement, located south of the range, being the town of Tanta (4300 m a.s.l.; 600 inhabitants). There are many lakes in the region, some of them of large dimensions that are currently used for an incipient fish-farming industry. In addition, the Yuracmayo dam was recently built for hydropower production. The main economic activity in the region is cattle raising, whilst agriculture remains a secondary and marginal sector.

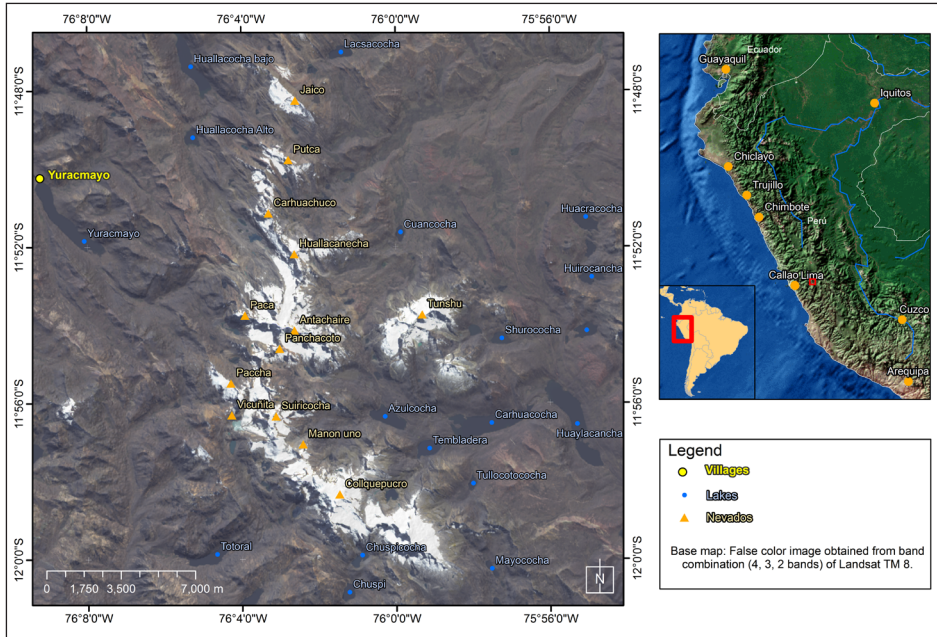


Figure 1. Study area.

3. Data and methods

The declassified US spy satellite Corona, KH-4 missions, collected a set of stereo images covering the Pariacacá mountain range on 7 June 1970 (Ruffner, 1995). The images provide historical perspective not available elsewhere, which has been used to obtain a close estimation of glacier extent in 1970. The three Corona strips were obtained from the US Geological Survey (USGS) EarthExplorer visor, with a reported nominal ground resolution of 7.62 m. The resulting orthoimages were georeferenced, identifying non-glacierised tie-points (moraines, lake spillways, river crossings, etc.), which were manually extracted from the panchromatic band of the 2018 Landsat OLI image (spatial resolution of 15 m) and 2018 PlanetScope imagery (spatial resolution of 3 m) in QGIS (v 3.4). Once properly registered, the orthoimages were interpreted visually, and the ice-covered area was delineated manually.

25 scenes of Landsat 5 (TM) and 8 (OLI) imagery were selected for the period 1987-2018 from the dataset available for the end of the dry period (July to September). Due to persistent cloudiness there were no images available for the years 1992 and 2012 (Table 1). The images were downloaded from the USGS website and were subjected to radiometric, geometric and atmospheric correction (López-Moreno *et al.*, 2014).

Table 1. Remote sensing images used in this study and their acquisition date.

Corona-KH4	Landsat 5-TM	Landsat 8-OLI	PlanetScope
1970-06-07	1987-07-27	2014-07- - 05	2018-05-30
	1988-07-29	2015-07-24	
	1990-07-19	2016-07-26	
	1991-07-06	2017-07-29	
	1993-06-25	2018-06-31	
	1994-07-14		
	1995-07-17		
	1996-07-03		
	1997-06-20		
	1999-07-12		
	2000-07-30		
	2001-08-02		
	2003-07-07		
	2004-07-09		
	2005-07-12		
	2007-07-02		
	2008-07-04		
	2009-06-05		
	2011-07-29		

Pixels covered by ice were identified, using the band-ratio between satellite-observed visible red (TM3 and OLI4 respectively) and shortwave infrared (TM5 and OLI6) digital numbers (Rakesh and Bolch, 2009), with a suitable threshold of 2.4 to classify ice cover. This threshold was selected for its maximum accuracy in the validation process (99% of the points were correctly discriminated as ice free/covered) performed with the PlanetScope imagery of 2018 (following the procedure presented by López-Moreno *et al.*, 2014). Despite avoiding the presence of fresh snow when selecting images, this was present for several years. In order to minimize the impact

of snow on the assessment of ice cover evolution we identified a pixel always free of ice, with the previous and the next year also ice free at the same pixel. Finally, in order to improve glacier delineation in 2018, we analysed five Level 3B scenes collected by the PlanetScope Dove satellite constellation on 30 May 2018, with a resampled ground resolution of 3 m (Planet Team 2017).

Given the absence of reliable long-term climatic data in the whole region, Reanalysis Data of temperature, precipitation, relative humidity, solar radiation and wind speed were used to consider temporal variability of the mentioned variables during the period of study. ERA 5 data (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>) at a horizontal resolution of 31 kilometres was used. Despite caution being required when using this data in regions with little or no observations, high resolution reanalysis data has been proven to properly reproduce observed trends, even in mountainous areas (Cornes and Jones, 2013). The reanalysis series from 1980 to 2018 and the ERA 5 data were aggregated annually for both the dry (May to September) and the wet (October to April) seasons. The existence of significant trends was tested using the non-parametric Mann-Kendall test (Kendall, 1975).

In order to analyse the topographic context of the location of the glaciers and the ablation hollows, Digital Elevation Models (DEMs) were used, constructed from ASTER Global Digital Elevation Map (GDEM) data (1 arcsec data, 30 m resolution) from the NASA EarthData depository (<https://gdex.cr.usgs.gov/gdex/>) and Radiometric Terrain-Corrected (RTC) ALOS PALSAR Global Radar Imagery (12.5 m resolution) provided by the VERTEX depository (<https://vertex.daac.asf.alaska.edu/>). Calculated from these DEMs were slope angle, aspect and potential incoming radiation under clear sky conditions using the “Solar Analyst” tool in ArcGIS.

4. Results

4.1 Evolution of surface covered by ice and its topographic context

According to the analysis performed with the Corona imagery, 68.2 km² were covered by ice in 1970, and this dropped to 53 km² in 1987 (Fig. 1). This yields a total loss of 22% of the glaciated area (0.84 km² yr⁻¹, 1.2% yr⁻¹) for the 1970-1987 period. During the period 1988 to 2018, the glaciated surface shrank to 30.5 km², which means a loss of 40% of the ice in the range in this 30-year period, and 55.3% since 1970. Figure 2 shows that the loss of ice is far from regular from one year to other, with specific years when losses are in the range of 2-3 km² (i.e., 1989, 1997 and 2005), while in other years glaciers in the area have shown no significant changes. The period 1988-1997 recorded the highest rate of ice loss (1.62 km² a⁻¹, or a 3%a⁻¹), with deceleration after 1998 (0.5 km² a⁻¹, or a 1.2% a⁻¹).

The loss of ice from one year to the other affects differently the different elevation bands and the areas with different exposition to solar radiation, as shown in Figure 3.

The loss of ice from 1970 to 1987 was exacerbated on high radiation slopes located below 5200 m a.s.l. In fact, during the first decade, more than 25% of ice losses occurred

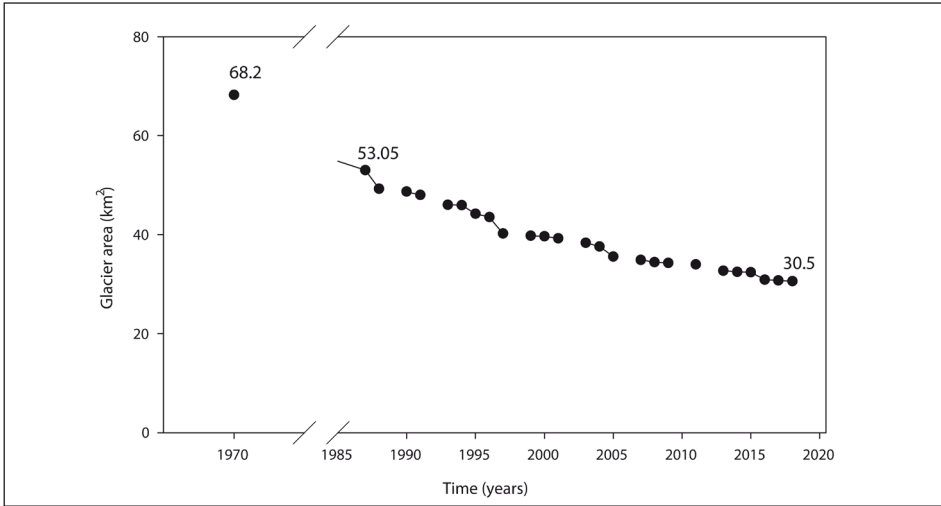


Figure 2. Surface of the Pariacacá Mountains covered by ice in 1970 and its temporal evolution from 1970 to 2018.

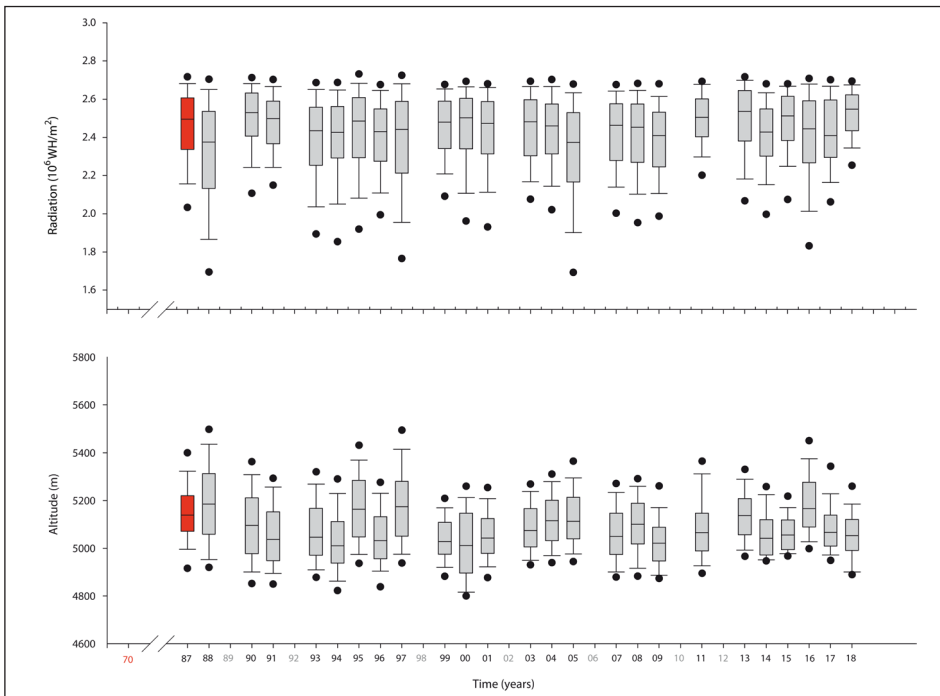


Figure 3. Frequency distribution of elevation and potential incoming radiation (under clear sky) on the glaciated areas that experienced shrinkage during the period 1988-2018. Years where ice cover could not be estimated have been aggregated to the following year. Line indicates the median, boxes the 25th and 75th percentiles, bars the 10th and 90th percentiles, and dots the 5th and 95th percentiles.

below 5000 m a.s.l., while this percentage was clearly reduced during the 21st century due to the lack of ice cover at these elevations. The highest quintile of elevation is also subjected to large interannual variability. Hence, some years there is a significant ice loss above 5200 m a.s.l. – with ice losses affecting even the summits (1988, 1995, 1997 and 2016) – while other years, the vast majority of ice losses occur only below 5200 m a.s.l. (i.e., 1999, 2014 and 2015). Similar variability is observed for potential incoming radiation (under clear sky conditions), with years where ice loss occurs in a very wide array of exposures to solar radiation (i.e., 1988, 1997, 2005 and 2016), while in other years ice losses are restricted to slopes that receive the most intense solar radiation (i.e., 1990, 1991, 1999, 2011 and 2018).

The existing contrasts in ice loss, depending on elevation and solar radiation, explain the changes that occurred in preferential aspect and altitude, where ice cover is distributed in the Pariacacá Mountains. Figure 4 shows such differences for the years 1970, 1987, and 2018. In 1970, ice cover was more evenly distributed in different aspects, compared to 1987 and 2018. In the most recent period (1987 to 2018) more than 50% of the ice in Pariacacá was found in the south and west aspects. In 1970, ice found in the south and west aspects made up 43% of the total area. Generalised loss of ice below 5000 m a.s.l. (shown in Fig. 3) is obvious, and a relative increase in concentration of the ice covered area for elevation above 5200 m a.s.l. is observed. Even when distribution of ice is similar, when comparing 1987 and 2018, notable differences exist, with a tendency to decreasing (increasing) concentration of the ice covered area of north and eastern (south and western) aspects, and a complete disappearance of ice at low elevations.

4.2 Ablation hollows and their spatial distribution

Ablation hollows are a significant feature of glaciers in the Pariacacá Mountains, as there is very high density in this region. Figure 5 shows two examples where their significant dimensions can be noted - more than 50 meters in diameter and a marked vertical development that, in several cases, reaches the bedrock. Ablation hollows may appear in the middle of glacier tongues or next to the snout. When the latter occurs, it

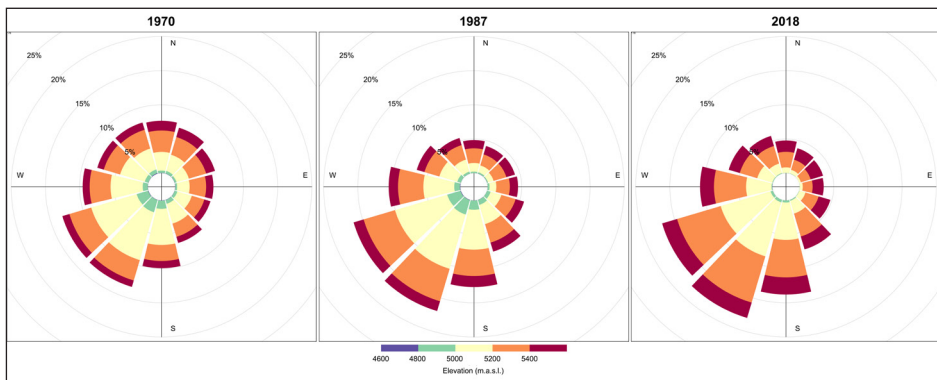


Figure 4. Distribution of area covered by ice at different aspects and elevation in 1970, 1987 and 2018.

triggers accelerated thawing. In the image from 2018, 78 ablation hollows were counted, distributed throughout the majority of glaciers in the range (Fig. 5). However, they are particularly concentrated (about 40% of the total number of glaciers) at medium elevations and in the southwest (SW) aspect. Despite the fact that they are preferentially

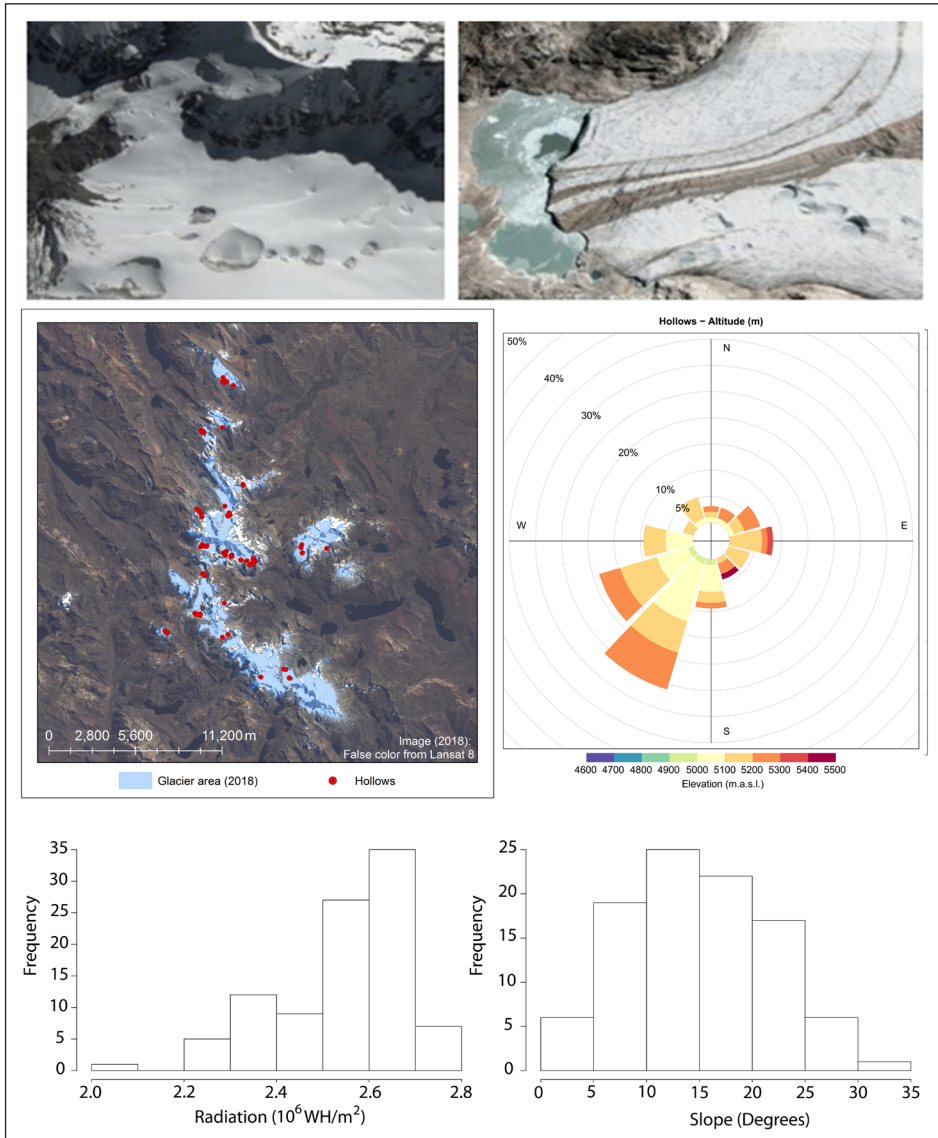


Figure 5. Upper panels: two examples of ablation hollows in glaciers of the Pariacacá Mountains. Middle panels: spatial distribution of ablation hollows (left) and distribution with regard to aspect, elevation. Lower panels: histograms informing about the distribution of ablation hollows depending on potential incoming radiation (left) and slope (right).

located in the SW aspect, the histogram of incoming solar radiation shows that they mostly develop in areas with high solar radiation levels. Moreover, 80% of the hollows are located in gentle slopes between 5 and 25°.

4.3 Recent climatic evolution

Figure 6 shows the temporal evolution simulated by ERA 5 reanalysis of the main climatic variables that control the energy balance of glaciers during the period 1980-2017. For this specific period, temperature did not show a significant trend during the dry (May-September) or the wet (October to April) seasons, whilst precipitation showed a decrease that is only statistically significant ($p < 0.05$) during the wet season. Relative humidity did not exhibit changes during the wet season but decreased during the dry months.

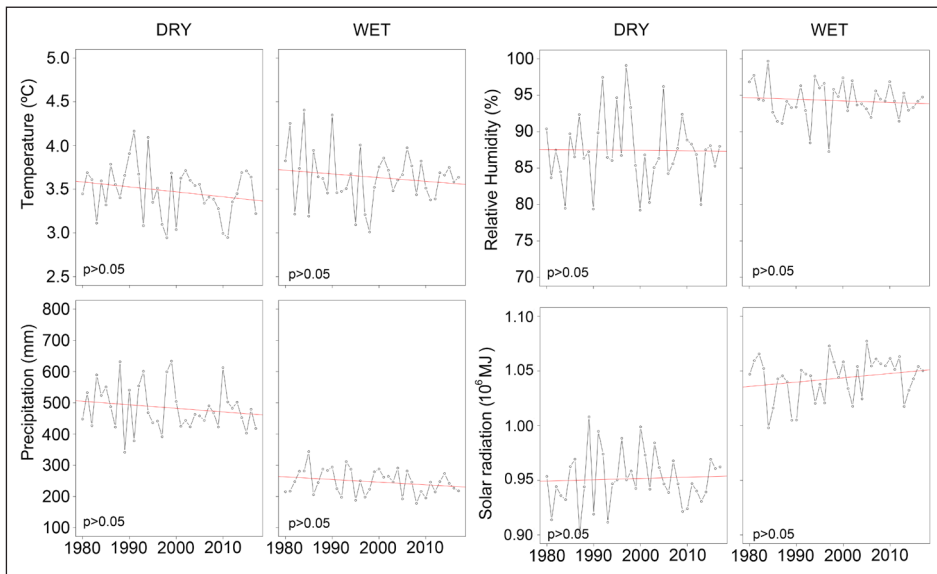


Figure 6. Annual evolution (1980-2017) of temperature, precipitation, relative humidity and incoming solar radiation for the wet and dry season from ERA-5 Reanalysis data.

5. Discussion and conclusions

Analysis of remote sensing images in the Pariacacá Mountains revealed that the area covered by ice has shrunk 55.3% since 1970 and 40% since 1987. These values exceed the rates of ice loss estimated in 40% for the whole Peruvian mountains since 1970 (ANA, 2014) but match with estimated glacier shrinkage for other mountain sectors where elevations do not exceed 6000 m a.s.l. (Veettil *et al.*, 2018; Burns and Nolin 2014). It is interesting to note that shrinking of Pariacacá glaciers is far from the 56% reported for the Huaytapallana range (1987-2013), despite being at the same latitude and less than 100 kilometres apart.

As observed in other mountains of Peru, there was a clear slowdown in the rates of ice shrinking after the late 1990's (Drenkhan *et al.*, 2018). This change corresponds to a lack of temperature trends in the tropical Andes since the analysed series began in 1980 (Vuille *et al.*, 2018; Schauwecker *et al.*, 2017). This behavior of temperatures, corroborated in the Pariacacá region with ERA-5 reanalysis data, has been associated with the cool phase of the Pacific Decadal Oscillation (PDO) since the early 2000s (Vuille *et al.*, 2018). Thus, this situation could potentially be reversed and could lead to accelerated glacier melt (Vuille *et al.*, 2015) if a new cycle of PDO – and the associated rise in temperatures – occurs.

Schauwecker *et al.* (2017) argued that glacier retreat post-2000 is a consequence of glaciers still reacting to strong warming that occurred before 1980, leading to many low-lying glaciers with a situation of clear imbalance. The increase of incoming solar radiation could be an additional explanation for sustained glacier shrinkage under recent stationary temperature conditions.

The spatial patterns of ice cover retreat have varied over time. During the period 1970 to 1987, glacier retreat mainly affected slopes with high radiation rates, located below 5200 meters. In the period 1987-2018, an extensive disappearance of the ice below 5000 meters occurred, with a subsequent concentration of surviving glaciers in the south and west aspects. Within the 1987-2018 period, a number of years showed ice thawing affecting both low irradiated slopes and the highest elevations, ultimately leading to the disappearance of ice from many summits of the mountain range. The current distribution of the Pariacacá glaciers (see Figure 4) very closely resembles the one depicted by (Veettil *et al.*, 2017, see Figure 2 of this article) for the Cordillera Vilcanota.

For the first time, the presence of ablation hollows at the ice surface has been quantified and its spatial distribution described. The presence of a total of 75 hollows has been confirmed, mainly concentrated in areas with gentle slope and high incoming solar radiation at mid elevations (5200-5400 m). Solar radiation seems to be the primary driver of their formation, creating concave surfaces that subsequently act as traps for solar radiation. Nonetheless, detailed analyses about the formation process and evolution, as well as their implication on glacier thawing, requires further research.

Climate scenarios available for the region for the next decades (López-Moreno *et al.*, 2014) suggest that ice loss will continue and even accelerate in the next years, leading to glaciers becoming a marginal component of the high mountain landscape and environment. As pointed out by many authors for other mountain areas of Peru (Vuille *et al.*, 2018), the deglaciation process will impact water quantity and quality in the region, affecting even Lima city. It is also likely to increase the spatio-temporal occurrence of natural hazards associated with lake level rise, slope instabilities and flash floods (Carey 2005; Haerberli *et al.*, 2016).

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